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14. ABSTRACT

Weston Weston Geophysical Corp., New England Research, Inc., and several geotechnical consultants conducted the New England Damage Experiment (NEDE) in central Vermont during July 2008. A series of five explosions using charges having yields of 135 and 270 lbs and three types of explosives were detonated in homogeneous low-fracture density granite. The goal of the experiment was to generate different amounts of rock damage around the source by using explosives with dramatically different velocities of detonation (VOD), ranging from 0.5 to 8.1 km/sec, and then relate the shear wave generation to the amount of damage. Increased VODs causes increased borehole pressures, which exceed the rock's compressive breaking strength, and results in more extensive fracturing of the source rock. This zone of highly fractured rock prevents the explosive gases from being able to drive long fractures. In contrast, slower VOD explosives generate fewer fractures around the borehole, but the explosive gases are able to enter the cracks and drive long fractures. Surface observation of the test site confirmed this as no fractures were found for the fast VOD explosive, multiple small cracks were seen for the middle VOD explosive, and large fractures with surface displacement were found for the slowest VOD explosive.

We have also used pre- and post-shot core analysis to quantify significant differences in the damage induced by the explosions. The extent of damage can be characterized by determining rock properties. Laboratory measurements of ultrasonic velocities, permeability, resistivity and porosity are sensitive to the microcrack density in the granite. Velocities are slower, permeabilities are higher, resistivities are lower and porosities are higher in the damaged intervals. These results are consistent with a microcrack scale fracture population that is enhanced by the blasts. This damage has been determined to extend vertically to as much as 6–7 meters from the explosive charge emplacement. Larger scale fractures are not apparent below the blasts, but are developed above the blast interval and they extend beyond the interval identified by the laboratory measurements.

Over 140 seismic sensors were installed to record the blast, ranging in distance from 5 m to 30 km. Peak particle velocity (PPV) studies found that the fastest VOD explosive, Composition B, expended much of its energy at the source pulverizing the surrounding rock. The middle VOD explosive, heavy ANFO, produced the largest PPV, while the slowest VOD explosive, black powder, produced PPV one-third the size of the ANFO PPV. Source scaling studies found the black powder shot produced seismic amplitudes up to an order of magnitude less than the ANFO and Comp B amplitudes above 5 Hz, but created Rayleigh waves similar in amplitude to those from the ANFO shot. The black powder shot produced larger Rayleigh and Love waves than the Comp B shot. The ANFO and Comp B shots generated similar amplitudes above 8 Hz, but the ANFO source Rayleigh waves were up to twice as large and the Love waves were up to three times as large as those from the Comp B shot. The seismic waves followed an almost identical travel path indicating that differences in the source region (e.g., possibly damage) are responsible for the variations in surface and shear wave energy. We continue to analyze the data to determine if the longer fractures from the black powder and ANFO shots appear to be responsible for the increased surface and shear wave energy.

15. SUBJECT TERMS

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QUANTIFICATION OF ROCK DAMAGE FROM SMALL EXPLOSIONS AND ITS EFFECT ON SHEAR-WAVE GENERATION: PHASE I—HOMOGENEOUS CRYSTALLINE ROCK

Mark Leidig[1], Randolph J. Martin[2], Peter Boyd[2], Jessie L. Bonner[1], and Anastasia Stroujkova[1]

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OBJECTIVES

Weston Geophysical Corporation and New England Research, Inc. and several geotechnical consultants collected a unique dataset of damage characteristics from explosions in hard, crystalline rock during July 2008. The NEDE project involved the detonation of five small (135 to 270 lbs) chemical explosions in relatively unfractured, homogeneous Barre granite in Vermont, USA. The objective of the project was to relate differences in rock damage from the explosions to variations in shear waves observed on local to regional distance seismic stations.

RESEARCH ACCOMPLISHED

The New England Damage Experiment

Site Selection. The NEDE was conducted at a granite quarry in Barre, Vermont, USA. The granite in this quarry has a low fracture density and typically forms large blocks. Barre granite has been a worldwide standard for homogeneous granite in commercial, monument, and industrial settings. We conducted pre-shot coring, crosshole velocity imaging, and acoustic televiewer imaging of the boreholes in order to characterize the emplacement media. Some of the results of these studies will be discussed later in this paper when compared to the post-shot damaged measurements.

Explosions. The NEDE included five single-blasthole explosions with total explosive weights ranging from 60 to 122 kg. (Table 1; Figure 1). The explosions were small in order to be contained in a single borehole, to reduce drilling costs, and to limit ground vibrations at nearby structures. Since an objective of this project was to relate rock damage to seismic phase generation, we attempted to design the experiments in order to fracture rock differently. Rock fracturing has been related to velocity of detonation. A slow explosive will often generate a large amount of gas that will drive crack formation; while a faster explosive will tend to rubbleize or powderize the material immediately adjacent to the borehole, and the powdered rock may impede the effects of gas-driven crackage. For more on these effects, the reader is referred to http://www.johnex.com.au/index.php?section=105 (last accessed in June 2009).

Table 1. NEDE origin parameters

Shot	Date	Origin Time	Latitude	Longitude	Elevation (m)	Depth (m)	Yield (kg)	Explosive	VOD (km/sec)
1	12-Jul-08	14:37:42.16	44.1577	-72.47848	509	8.3	60.8	Black Powder	0.53
2	12-Jul-08	16:02:05.02	44.158	-72.47813	509	10.7	61.5	ANFO/EMUL 50:50	4.76
3	12-Jul-08	17:30:40.73	44.1578	-72.4777	503	10.7	61.7	COMP B	
4	12-Jul-08	19:16:15.01	44.1575	-72.47797	508	12.8	122.2	ANFO/EMUL 50:50	4.89
5	12-Jul-08	20:50:12.77	44.1575	-72.47757	503	12.8	122.5	COMP B	8.10

Black Powder. With the assistance of Mr. Tim Rath of Maxam-North America, we designed the NEDE to have a wide range of VODs (Figure 2). For Shot 1, we detonated 60.8 kg of black powder (Figure 3) at a centroid depth of 8.3 meters in a 22.86 cm diameter borehole. The explosives column extended approximately 1 meter above and below the centroid. Schist gravel, with a diameter of 1¼ cm, was used to stem the boreholes. Black powder was used exclusively for hundreds of years in mining and military applications. Today, the use of black powder as an explosive has diminished considerably, but it is often used to detach rock along pre-existing fractures such as in the Vermont slate district. The VOD was measured at 0.53 km/sec for Shot 1 (Figure 2); however, we note that the black powder typically "deflagrates" rather than "detonates" unless under highly confined conditions.

Heavy ANFO. Shots 2 and 4 consisted of a 50:50 blend of Ammonium Nitrate Fuel Oil (ANFO) and Emulsion explosives. The mining industry typically refers to this blend as "Heavy" ANFO, because the mixture increases the density allowing more explosives to be loaded into a borehole. It also helps to waterproof the explosive as compared to pure ANFO. Heavy ANFO is often used in today's commercial blasting industry because of low cost (e.g., $2/kg) and abundant gas formation that helps fracture the rocks efficiently. Shot 2 consisted of 61.5 kg of Heavy ANFO detonated at a centroid depth of 10.7 m while Shot 4 had almost double the explosives at a centroid depth of 12.8 m. The thicknesses of the explosive columns were approximately 1 and 2 meters for Shots 2 and 4, respectively. Both Heavy ANFO shots were detonated in 22.86 cm diameter boreholes with schist stemming. The measured VOD was 4.76 km/sec and 4.89 km/sec for Shots 2 and 4, respectively.

Figure 1. Photos of the test bed where the NEDE explosions (blue circles) were detonated. Also shown are three near-source station locations (red squares) and the estimated elastic radii (red dashed circles).
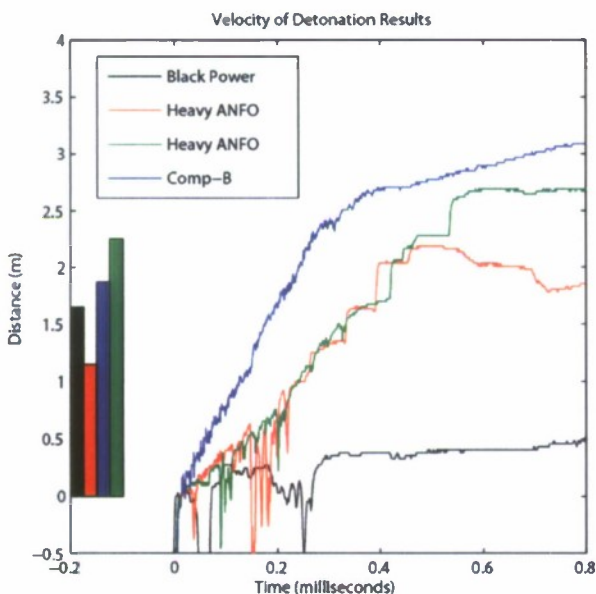

Figure 2. Velocity of detonation recordings for four NEDE shots. A fifth shot was not recorded using VOD equipment. The raw VOD data were aligned so that the approximate start of the resistance wire burn was at distance=0. Also shown are the lengths of the explosives column (bars at left) which correlate well with the VOD data.

Composition B. Shots 3 and 5 consisted of Composition B, a military grade explosive. According to GlobalSecurity.org, "COMP B explosives are made from TNT, RDX, and wax, such as 59.5 percent RDX, 39.5 percent TNT and 1 percent wax. Desensitizing agents are added. Composition B is used by the military in land mines, rockets and projectiles. Cast Composition B has a specific gravity of 1.65 and a detonation velocity of about 25,000 fps and is used as a primer and booster for blasting agents."[1] We had the COMP B charges cast as 45 kg cylinders of 19.1 cm diameter and 94 cm length (Figure 3). One cast charge was used for Shot 3 and two for Shot 5. Because of the space between the 19.1 cm charge and 22.86 cm diameter borehole wall, the casts were lowered into bulk emulsion to ensure adequate coupling, thus resulting in final explosive yields of 61.7 kg and 122.5 kg for Shots 3 and 5, respectively. The charges were placed at the same centroid depths as the Heavy ANFO shots 2 and 4. The VOD for Shot 3 was not measured; however, for Shot 5, the VOD was 8.1 km/sec.

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[1] http://www.globalsecurity.org/military/systems/munitions/explosives-compositions.htm

Figure 3. Photo of the explosives used in the NEDE. (Left) Packages of "Polvara Negra" or black powder. (Middle) Containers of pre-mixed Heavy ANFO (50:50 ANFO:Emulsion). (Right) A cast charge of Composition B.

Instrumentation. Instrumentation deployed to record the NEDE explosions consisted of two primary groups: (1) near-source (<1.5 km) acceleration and velocity instruments and (2) near-regional distance (1.5-30 km) vertical component geophones and three-component (3C) high-frequency seismometers deployed along northeast and southeast profiles (Figure 4). Numerous additional regional (> 30 km) seismic stations that comprise seismographic networks in New England (e.g., New England Seismic Network) also recorded the explosions (Figure 5). The design of this instrumentation plan was intended to document the generation and propagation from near-source to near-regional distances of both the compressional and shear energy from the single blasthole explosions.
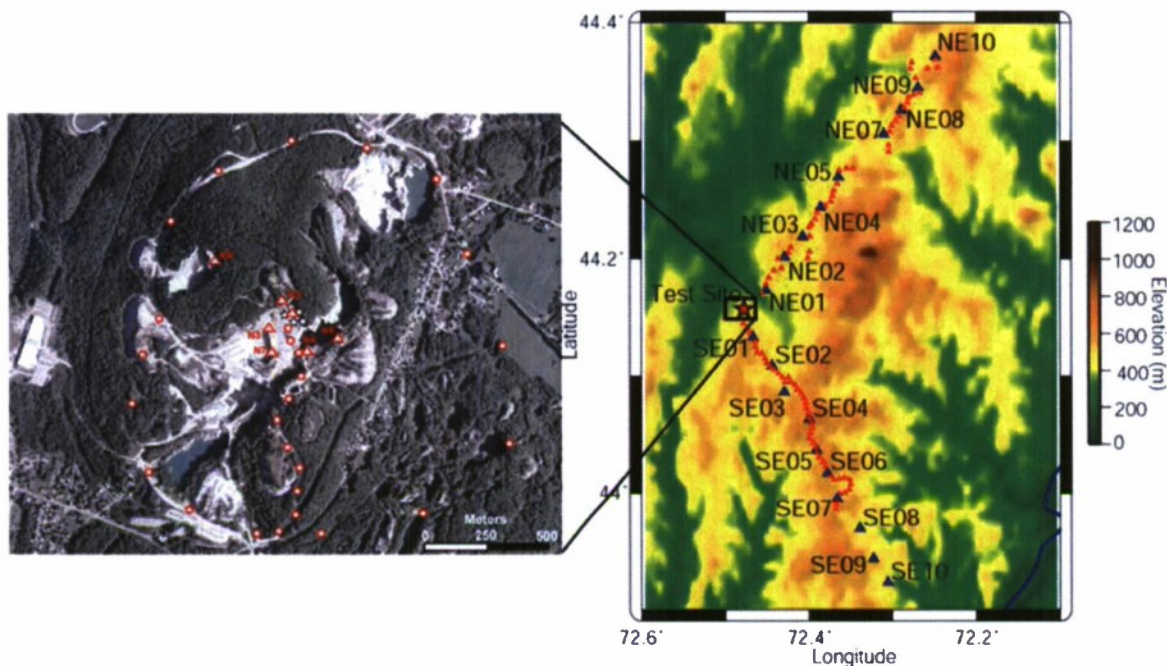
Figure 4. Location of the NEDE explosions and seismometers. (Left) Satellite imagery of the test site and near-source instrumentation. Circles are RT125 or "Texan" single-component (1C) geophones. Triangles are three-component (3C) accelerometer/velocity sensor sites within 600 meters of the test site. (Right) Local distance instrumentation. Blue triangles represent either L22 (southeast profile) or L4 (northeast profile) 3C short-period velocity sensors, while the small red triangles are 1C Texans.

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Preliminary Observations: Seismic

Regional Observations. Figure 5 shows the data from Shots 4 and 5 (see Table 1 for info) at station PKME in Maine, which was located 270 km from these two 125 kg explosions. While the signal-to-noise ratio is small, the data show that the Lg amplitudes were larger for the Heavy ANFO Shot 4 than the COMP B Shot 5. Also of interest is the impulsive arrival at a group velocity of 4 km/sec (possibly Sn?) on the Shot 4 records that is not observed for Shot 5. It is interesting to note that while there were visible cracks on the surface after the Heavy ANFO Shot 4, there were none for the COMP B shot.
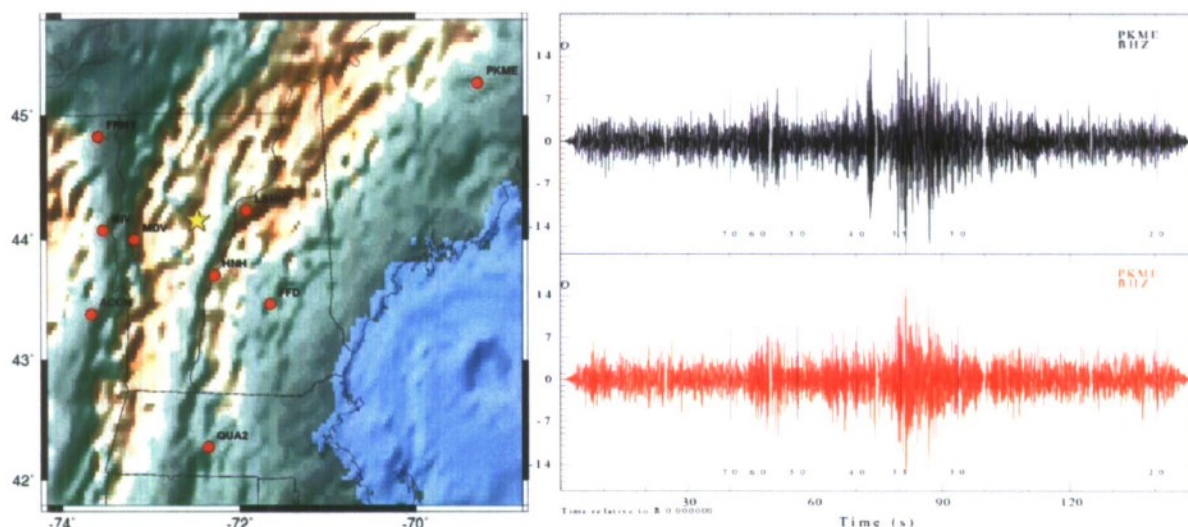

Figure 5. Regional stations (left) that recorded at least one of the NEDE explosions. The signals were recorded as far away as 270 km at station PKME (right).

Spectral Ratios. Empirical source scaling relations using the near-source and local data were compared for the three different explosive types in five different explosions (Table 1). In most cases, spectral ratio data from each distance range document similar scaling. The source scaling studies show that the 61 kg black powder explosion was deficient in high-frequency energy when compared to the 62 kg Heavy ANFO and COMP B charges (Figure 6). At frequencies above 5 Hz, the black powder explosion amplitudes were up to an order of magnitude smaller than the faster VOD explosives. The black powder explosion generated surface waves that were equivalent to the ANFO explosion at frequencies below 5 Hz. The Rayleigh-waves generated from the 61 kg black powder shot were larger than the equivalent COMP B explosion. The black powder charge generated larger-amplitude short-period Love-waves than the COMP B explosion for all azimuths studied, which may provide important data in addressing the continuing problem of determining the source of S-wave generation from explosions. The Mueller-Murphy (1971) explosion source model cannot explain the black powder effects using standard empirical relationships between explosion yield and source elastic and cavity radii and static pressures, and will require more detailed study after the damage zones from the explosions have been quantified and the nominal explosion pressures have been estimated.

Comparisons of the Heavy ANFO and COMP B explosions show small differences at body-wave frequencies (> 8 Hz) and larger effects at surface-wave frequencies. The slower VOD Heavy ANFO explosions generated larger-amplitude Rayleigh waves (up to a factor of 2x larger) and Love waves (as large as 3x) than the equivalent COMP B charges (Figure 6). These differences are not modeled adequately using the Mueller-Murphy (1971) source. We propose to use the results from this source scaling study to relate seismic phase generation, particularly for S-waves (e.g., Lg, Love waves), to damage effects from the explosions.
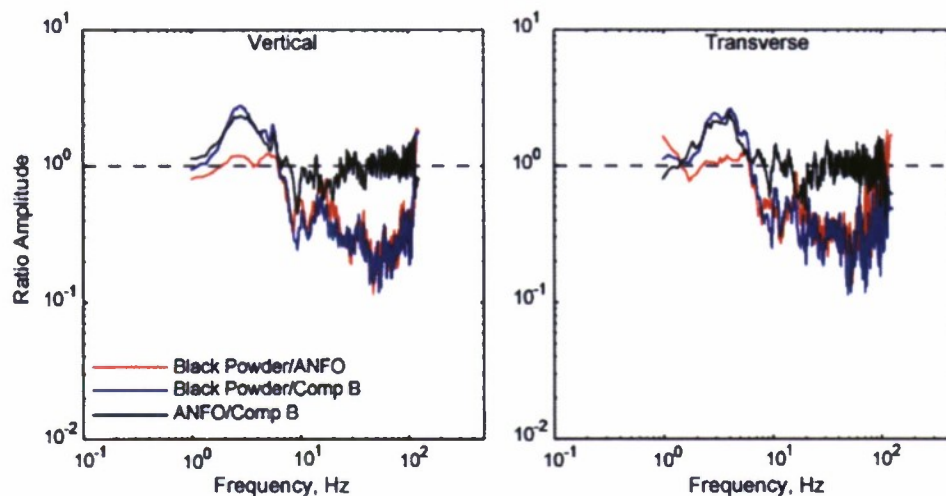
Figure 6. Summary of the mean spectral ratios for vertical (left) and transverse components (right) for different shot combinations (e.g., Black power/ANFO, Black Powder/COMP B, ANFO/COMP B).

Preliminary Observations: Damage

The Rock of Ages granite quarry was selected for the explosion study because the Barre Granite is homogeneous with a low fracture density. Although the granite at the site is massive, it is anisotropic. The anisotropy is a direct result of the rift plane common in most granites. The rift plane is due to the preferred orientation of microcracks. Mineral alignment may also play a small role in the anisotropy. The orientation of the rift at the quarry is well documented and varies between 30° and 60° (Engelder et al., 1977). At the test site, the range of variability in the rift was much smaller, consistently at or near 30°. An examination of the quarry faces in the nearby open pits southeast of the test site show well developed quarry working faces at 30°.

Visible fractures were observed on all quarry faces, and at the site of this study, the outcrop fracture spacing was on the order of 4 to 5 m. The fractures are typically clean and planar with very little brecciation. In a few cases, the fractures appear healed with indications of small scale slip along some of them.

The Barre Granite is a gray fine to medium grained granodiorite. A photomicrograph of the Barre is shown in Figure 7. The composition of the granite is microcline (21%), orthoclase (35%), quartz (27%), biotite (9%), and muscovite (6%) with various accessory minerals (VT Geological Society, web 2008). The composition of the granite is uniform throughout the test site (Richter, 1987).

Visual examinations of the surface after the blasts showed radial fractures from the Black Powder and Heavy ANFO Shots 1, 2, and 4, while COMP B Shots 3 and 5 produced no surface cracks. To further quantify the change in rock properties resulting from the explosions, coreholes were drilled before and after the detonation of the explosives. Two control holes were cored adjacent to the emplacement holes for Shots 2 and 5, (see Table 1). Subsequent to the detonations, three additional holes were cored. One post-shot corehole was adjacent to the 61.5 kg Heavy ANFO shot and two were cored adjacent to the 122 kg shots. Core were collected, documented, and analyzed at NER. There was complete core recovery from the two pre-shot coreholes, and few native fractures were observed. Post-blast core recovery was good overall, but the cores were fragmented and partially incomplete near the blasts. The intervals above the emplacement depth had less fragmentation. There were no large scale induced fractures observed below the shot points. The fracturing is illustrated in Figure 8, which shows the pre-shot core from CH-1 and the post-shot core from the adjacent CH-3 corehole. It is noteworthy that the most intense fragmentation in this section of core occurs below the emplacement interval.

Figure 7. Photomicrograph of Barre Granite thin section taken at a depth of 14.2 m in the CH-1 core. View taken with polarized light. The plane of the section is perpendicular to the rift plane.

Figure 8. Comparison between cores recovered from the pre-shot and post-shot coreholes adjacent to Shot 2. The cores span the emplacement depth from 10.1 to 11.3 m.

Figure 9 shows an interesting feature observed in the post-shot cores, blast induced disking. It developed over a 1.8 m interval in CH-4. In addition, visual observation of the post-shot cores showed gross changes in the appearance of the core near the working point. The native rock is bluish gray, while the rock recovered near the blasts is lighter colored. The change in appearance is likely due to shattering or crushing of the grains. Further characterization of this observation requires thin section, SEM, and pore structure modeling analysis.

As part of the pre-shot site characterization, a borehole geophysical logging program was undertaken by Hager-Richter Geoscience, Inc. to provide details of the granite *in situ*. Oriented acoustic televiewer logs, optical televiewer logs, and caliper logs were run. The logs verify that there are few fractures. An example of a fracture identifiable in the logs recorded in CH-1 is shown in Figure 10. As the logs were oriented with respect to magnetic North, they were a valuable aid in orientating of the rift plane (using ultrasonic velocity measurements) with respect to fractures. That orientation coincides with the surface observations and reference publications.

The suite of measurements included velocity to identify the orientation of the rift plane, continuous linear velocity scans where possible, permeability and electrical resistivity measurements as a function of pressure, grain and bulk density, porosity calculations, and thin section image analysis. All measurements were performed on oriented

specimens relative to the rift plane. The most detailed data are available for the pre-shot CH-1 and post-shot CH-3 coreholes.
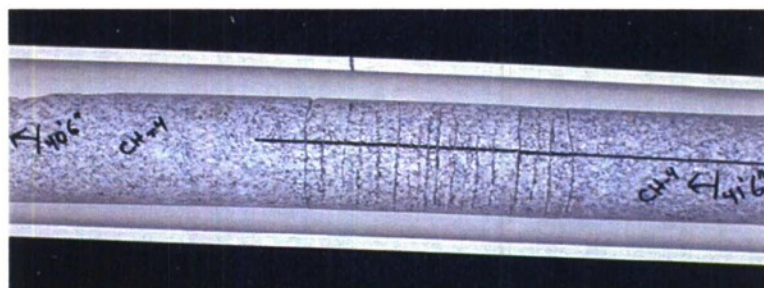

Figure 9. Core disking at 12.5 m depth in CH-4. This corehole is adjacent to Shot 5, which had an explosives emplacement interval between 11.9 m to 13.7 m.
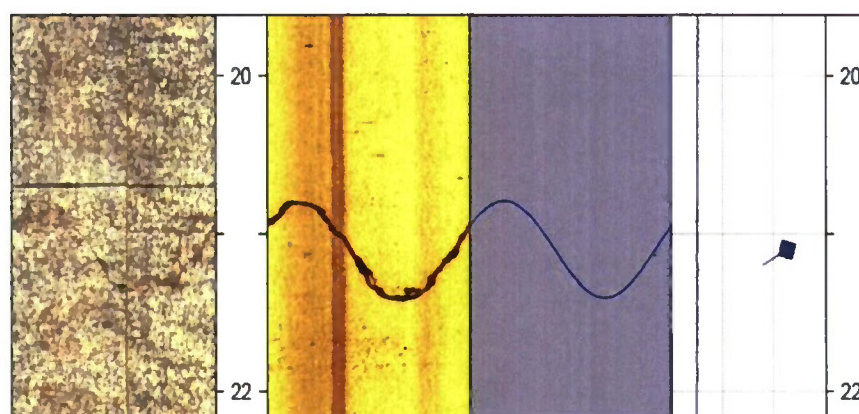

Figure 10. Example of fracture identified by Hager-Richter borehole log run in CH-1. Left to right: Optical Televiewer, Acoustic Televiewer, Fracture outline on borehole wall and tadpole plot showing orientation and dip of fracture. Depths are shown in feet.

Bulk Properties. The Barre Granite is mineralogically homogeneous over a wide area. Little variability in bulk density and grain density were noted, so limited measurements were carried out on the pre-shot specimens. Representative data are presented in Table 2. The data show small variability in the undisturbed cores, but a reduction in density and increase in porosity over the blast interval in CH-3. These changes are most likely due to an increase in the size and density of microcracks.

Table 2. Bulk properties of Barre Granite

	Pre-Shot	Post-Shot
Grain Density, g/cm^3	2.66-2.76	2.66-2.76
Dry Bulk Density, g/cm^3	2.63-2.65	2.60-2.63
Porosity, %	0.7-1.3	1.4-2.5

Velocity Data. Velocity measurements were performed by transmitting ultrasonic compressional and shear waves through diametral chords in the recovered core using a bench top apparatus. The cores were rotated between the velocity transducers, and data were collected, until the acoustically fastest chord was identified. The "Fast" chord is parallel to the rift plane and the chord oriented at 90 degrees to it is the "Slow" direction. Since all measurements on sub cores are oriented with respect to the rift plane, identifying the orientation of the rift in all of the cores facilitates proper sample preparation.

Velocity measurements were also carried out on sections of core recovered from post-shot coreholes CH-3, 4, and 5. The coreholes were adjacent to the 61.5 kg Heavy ANFO, the 122 kg Comp B, and the 122 kg Heavy ANFO shots, respectively. Figure 11 shows comparisons of pre- and post-shot compressional wave velocities as a function of depth in the corehole near the 61.5 kg heavy ANFO shot. Open red diamonds show the pre-shot data, while solid green diamonds show the post-shot velocities. For reference, the centroid depth of the charge was at 10.7 m. The post-blast velocities are significantly lower near the working point; for example, "Fast" velocities of 3,300 m/sec were observed near the working point compared with the pre-shot velocities of 4,300 m/sec, a decrease of 23%. Anomalous behavior was observed below the working point as the post-shot velocities exceed the pre-shot velocities. There is no obvious explanation for this observation, and additional measurements of composition and density need to be carried out to address this effect.

The *P*-wave anisotropy, the difference between the "Fast" and "Slow" *P*-wave velocities, divided by the "Fast" *P*-wave velocities, is presented as a function of depth in Figure 12. The anisotropy remains relatively constant, near 17%, at all depths. There is little indication that the anisotropy was affected by the explosion.
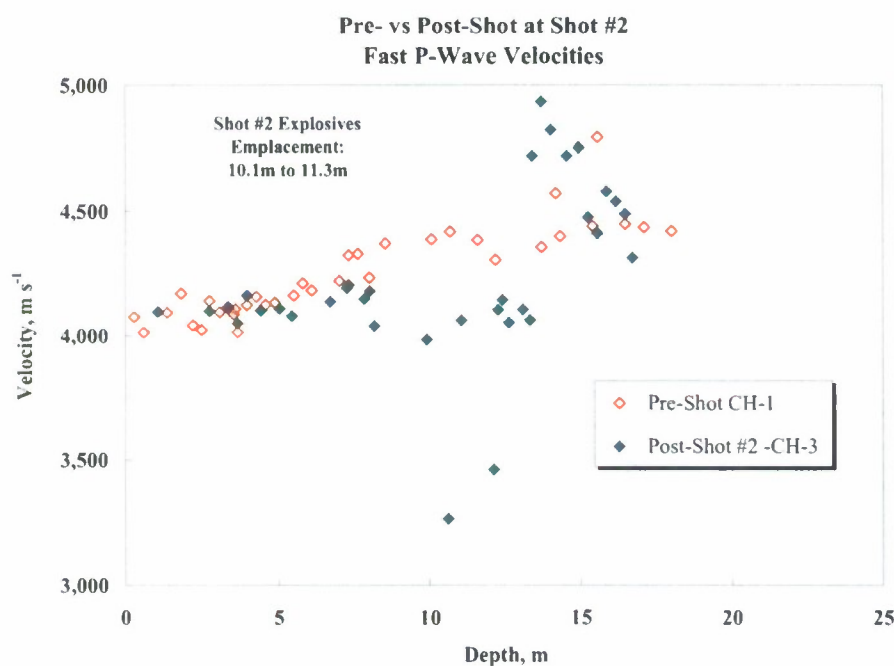
Pre- vs Post-Shot at Shot #2
Fast P-Wave Velocities

Figure 11. "Fast" compressional wave velocity vs. depth at Shot 2 location. Data from pre- and post-shot coreholes are plotted.

CONCLUSIONS AND RECOMMENDATIONS

The NEDE provided a unique test of explosions with variable VOD (0.5 to 8.1 km/sec) in order to generate variable damage. The slow VOD Black Powder and medium VOD ANFO shots produced radial cracks on the surface; the fast VOD COMP B shots did not. NER has observed intriguing characteristics of the microscopic damage from the cores near the shot points including changes to density and porosity, color changes, and velocity decreases. The seismic data from near-source, local, and regional distances suggest more Rayleigh and SH energy were generated by the Black Powder and ANFO shots than the COMP B. Our preliminary assessment of the experimental data suggests that there could be a direct correlation between damage and *S*-wave generation. For future studies, we will continue to quantify the bulk properties, density, and porosity of the rocks before and after the explosions.

Pre- vs Post-Shot at Shot #2
P-Wave Anisotropy
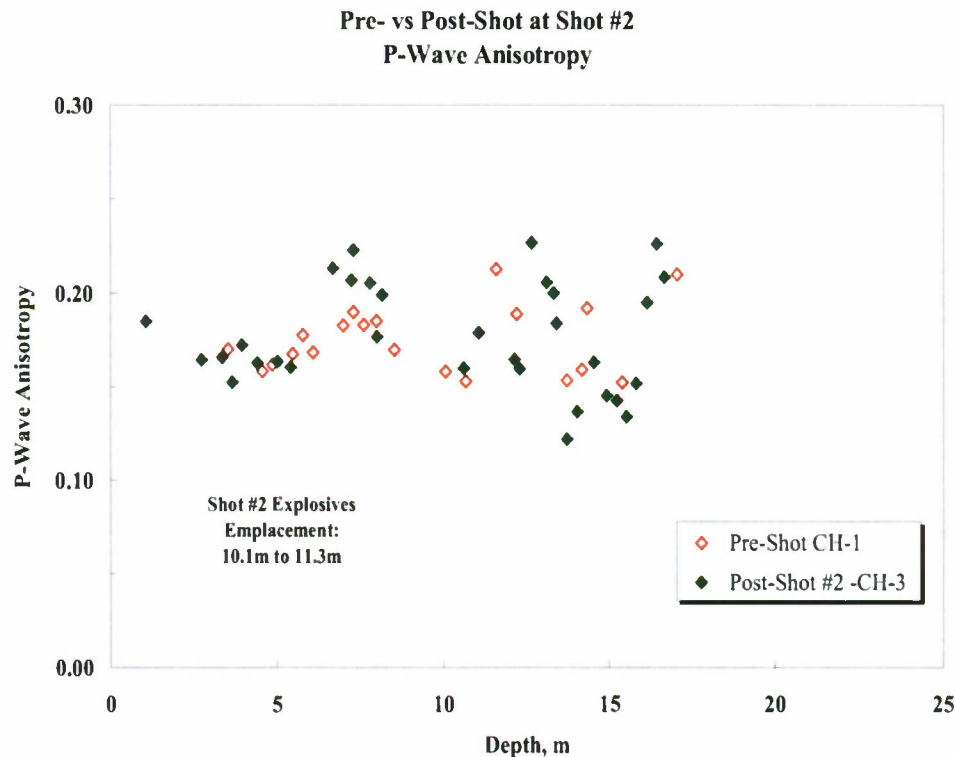
Figure 12. Compressional wave velocity anisotropy vs. depth at Shot 2 location.

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Richter, D. A. (1987). Barre granite quarries, Barre, Vermont, in *Geological Society of America Field Guide – Northeastern Section*, 239–242.